IJSPT

ORIGINAL RESEARCH

THE INFLUENCE OF HEEL HEIGHT ON MUSCLE ELECTROMYOGRAPHY OF THE LOWER EXTREMITY DURING LANDING TASKS IN RECREATIONALLY ACTIVE FEMALES: A WITHIN SUBJECTS RANDOMIZED TRIAL

Kelly M. Lindenberg, PT, MSPT, PhD[1]
Christopher R. Lefever, PT, DPT, SCS, CSCS[2]
Kristin Andreyo, PT, DPT[3]
Ryan Vaughan, PT, DPT[4]

ABSTRACT

Background: An increased risk of ACL injury has been shown in female athletes who land from jumping maneuvers with knee angles close to extension and in those who demonstrate a hamstring-to-quadriceps muscle recruitment imbalance.

Hypothesis/Purpose: The purpose of this study was to determine if added heel lift height would alter electromyography (EMG) magnitude and timing of the quadriceps (vastus medialis, vastus lateralis), hamstrings (semitendinosus, biceps femoris) and gastroc (medial gastroc, lateral gastroc) musculature during forward jump and drop-rebound jump landing tasks in females. The authors hypothesized increased heel lift height would promote recruitment of the hamstring and gastrocnemius muscles and increase the time to peak muscle activity in the quadriceps muscles.

Study Design: Prospective randomized trial

Methods: 60 recreationally active females participated. Participants performed five repetitions of forward jump and drop-rebound jump landing tasks while wearing different heel lifts heights (0, 12, 18, 24 mm) placed on the under-side of an athletic shoe. Task order and heel lift height were randomized. Dependent measures were average magnitude of muscle recruitment (AMR), peak magnitude of muscle recruitment (PMR), and time to reach PMR for six lower extremity muscle groups as measured by surface EMG.

Results: Repeated measures ANOVAs were used to determine the influence of heel lift height on the dependent measures. There were no signficant differences in the AMR, PMR, or time to reach PMR with the four different heel heights during the landing maneuvers, with one exception. A significant difference was found in the time to achieve PMR in the semitendinosis muscle during a forward jump landing ($p = .024$). Post hoc analysis found significant differences with both the 18mm and 24mm heel lift height compared to 0mm.

Conclusions: Utilization of larger heel lifts (18mm and 24mm) to influence landing biomechanics may be of potential benefit; however, only when performing forward jump landing tasks. Further investigation into the protective effects of a quicker onset of semitendinosis peak magnitude is warranted.

Level of Evidence: 2

Key Words: ACL, electromyography, heel lift, kinematics, landing

[1] Slippery Rock University, Graduate School of Physical Therapy, Slippery Rock, PA, USA
[2] Memorial Hermann IRONMAN Sports Medicine Institute, Katy Sports Park, Houston, TX, USA
[3] Encompass Health Rehabilitation Hospital of Sewickley, Sewickley, PA, USA
[4] Encompass Health Rehabilitation Hospital of Altoona, Altoona, PA, USA

Conflict of Interest Statement: The authors affirm that they have no conflicts of interest to disclose.

CORRESPONDING AUTHOR
Kelly M. Lindenberg
Slippery Rock University
Physical Therapy Building
1 Morrow Way
Slippery Rock, PA 16057
E-mail: Kelly.lindenberg@sru.edu

DOI: 10.26603/ijspt20190866

INTRODUCTION

Researchers have consistently demonstrated that anterior cruciate ligament (ACL) injuries occur more frequently in female compared to male athletes.[1,2,3,4,5] However, the basis of this gender disparity remains poorly understood. Although many theories have been proposed,[6,7,8,9] no evidence exists that supports a single cause for the female's propensity towards ACL injury. Furthermore, researchers have struggled to find proven methods to limit or prevent these injuries.[10]

Risk factors for sustaining ACL injuries have been divided into four general categories: environmental, anatomical, hormonal, or biomechanical.[6] Many of these risk factors cannot feasibly be altered. However, given the ability to change joint kinematics and muscle activity, many researchers have focused on the biomechanical risk factors utilized by female athletes during sports maneuvers.[7,8,9,11,12,13,14,15,16] Researchers have demonstrated that females repeatedly utilize an extension-biased knee landing pattern in a variety of sport maneuvers.[11,13,14,17,18,19] The ramifications of landing with the knee closer to extension include increased EMG activity of the quadriceps,[10,13,20,21] increased anterior tibio-femoral shear,[21,22,23] increased vertical ground reaction forces,[14,24] and a decrease in EMG activity of the hamstrings.[13,22] Each of these characteristics are thought to increase ACL injury risk.[23,25,26]

ACL injury prevention programs have been used to favorably influence kinematic patterns during varied landing tasks in female athletes.[27,28,29,30,31,32,33] However, many of these programs require a substantial time investment of 90-minutes or more several times per week,[14,27,28,29,35,36] often requiring greater than six-weeks of consistent training.[27,28,29,34,35,37,38] This time component is apt to have negative effects on compliance, which has been demonstrated to be a substantial factor in the overall success of a program.[33,35] Furthermore, the duration of the protective effects of these training programs after cessation of participation is unknown. Conversely, some challenge these prevention programs, refuting the proposed benefits and arguing a lack of effect with reduction of non-contact female athlete ACL injury.[10] Vescovi et al suggests these programs do not readily improve athletic performance, perhaps further hindering compliance from the perspective of coaching staff with dense team training schedules.[38]

A prevention strategy that requires minimal time and effort yet can still favorably alter knee biomechanics would be of substantial benefit to female athletes. To this end, evidence exists that increased heel height alters lower extremity biomechanics[39,40,41,42,43,44,45,46,47,48] and muscle activity[41,44,45,46,47] during gait,[39,40,41,42,43,45,46] sit to stand[44] and jump-landing tasks.[47,48] Both static-standing and dynamic gait analyses have demonstrated increased knee flexion angles with increased heel height.[40,41,42,43,47] Lindenberg et al[47] demonstrated that a 24 mm heel lift significantly increased knee flexion angles at initial contact and maximal excursion, as well as slowed the rate of excursion during a single forward jump landing maneuver. Further research demonstrated that a 24 mm heel lift significantly decreased peak vertical ground reaction force when landing from a forward jump landing maneuver.[48] These kinematic changes associated with added heel lift height suggest that the incorporation of a heel lift may offer an alternative strategy for altering knee kinematics during sporting activities. However, no research has been performed to explore the effect of added heel lift height on muscle recruitment patterns during landing maneuvers.

Therefore, the purpose of this study was to determine if added heel lift height would alter electromyography (EMG) magnitude and timing of the quadriceps (vastus medialis, vastus lateralis), hamstrings (semitendinosus, biceps femoris) and gastroc (medial gastroc, lateral gastroc) musculature during forward jump and drop-rebound jump landing tasks in females. The authors hypothesize that added heel lift height will significantly slow the onset of quadriceps recruitment and increase the magnitude of hamstring and gastrocnemius recruitment.

METHODS

A convenience sample of 60 recreationally active females between 18 and 25 years of age was recruited for this study. Recreationally active was defined as engaging in aerobic and/or anaerobic exercise for an average of four to five hours per week. To be included in the study, all participants declared the ability to perform a forward jump and drop-rebound jump landing onto the dominant lower extremity. However, subjects were not asked to perform these activities until after informed consent had been obtained. Individuals who had previous surgery to their lower extremities or who had an acute lower extremity injury within the six months prior to the study were excluded. For the purposes of this study, "acute" was defined as suffering an injury to the lower extremity that required the use of an assistive device for more than one day. Furthermore, individuals who wore foot orthotics were excluded from the study. Data from a previously conducted pilot study was used to calculate the required sample size for this current study. G* Power software (G*Power 3.1.10, Dusseldorf, Germany) was used to determine that the sample size needed to achieve statistical power was 60 subjects. This study was approved by the Institutional Review Board at Slippery Rock University.

The study utilized a randomized block design. All data collection was performed in one session. Testing took place in a motion analysis laboratory at the university. After the collection of demographic information and maximum voluntary isometric contraction (MVIC) data, all subjects completed two landing tasks: landing from a 40 cm platform and a forward jump at a distance of 45% the subject's body height. The subject completed these tasks under four different heel lift height conditions: 0mm, 12mm, 18mm, and 24 mm. Prior to beginning the two landing tasks, the investigator randomly determined the order of heel lift application in order to diminish bias. Randomization was performed by drawing the four different heel lift conditions, which were written on slips of paper and placed in a hat. Previous studies[47,48] utilized similar landing tasks to those presented here to analyze lower extremity kinematics in athletes. This allowed for direct comparison to previous work.

Dependent Variables

Six lower extremity muscle groups were examined through the use of surface EMG including the vastus medialis obliquus (VMO), vastus lateralis (VL), biceps femoris (BF), semitendinosis (ST), medial gastrocnemius (MG) and lateral gastrocnemius (LG) regarding the following variables:

(1) Magnitude of muscle activity at initial contact with landing (expressed as a percentage of the MVIC)

(2) Magnitude of peak muscle activity (expressed as a percentage of the MVIC)

(3) Time to achieve peak muscle activity with landing

Independent Variable

Heel lift height with four levels: 0mm, 12mm, 18mm, 24mm.

Instrumentation

Four footswitch triggers (Noraxon DTS Footswitch probe with four FSR sensors, Scottsdale, AZ) were utilized to mark initial contact during landing to assist with data reduction procedures.

Surface electrodes and wireless telemetric electromyography (EMG) system (Telemyo DTS desktop receiver; Noraxon, Scottsdale, AZ) were used to capture EMG data, from which muscle recruitment and timing were later extracted.

A System 4 Pro Dynamometer (Biodex Medical Systems, Shirley, NY) was utilized to standardize position and stabilization while measuring MVIC of each muscle group.

Heel lifts (G&W Heel Lift Incorporated; Cuba, MO) were injection-molded PVC vinyl lifts 6mm and 12mm in height. Two heel lifts were combined with double-sided tape provided by the manufacturer to achieve the 18 and 24mm height. The investigator affixed the appropriate heel lift to the under-surface of the subject's shoe with one inch wide carpet tape (Ace Hardware Corp.; Oak Brook, IL).

Collection of data

Data collection was completed in one session. Each subject reported to the motion analysis laboratory for testing. Subjects were oriented to the instrumentation and all procedures were thoroughly explained. Informed consent procedures were completed, and demographic information was recorded.

All data were collected from the subject's dominant lower extremity. Lower extremity dominance was determined using a self-selection strategy. Specifically, subjects were asked to perform a single leg landing from a 20 cm box. The leg the subject landed on for two out of three trials was defined as their dominant lower extremity.

Subjects were asked to demonstrate the ability to perform both the forward jump and drop-rebound jump landing tasks without restrictions. If an individual was unable to do so, then he or she was excused from participation in the study.

Subjects were fitted with four foot switches on the plantar surface of the dominant lower extremity. The foot switch consisted of sensors that were secured to the foot plantar surface via double sided tape. Sensors were located on the heel, first metatarsal head, fifth metatarsal head, and pad of great toe per manufacturer recommendations.

Subjects donned a standardized athletic shoe (New Balance, Boston, MA). Throughout the data collection session, the various heel lift heights were affixed to the outside/bottom of the subject's shoes. The manufacturer established the use of two adjoined heel lifts as an acceptable use of the product. Specialized adhesive for this purpose was provided with the purchase of the heel lifts. Subjects were not made aware of the order of the heel lift heights that were applied for each jump.

Next, surface electrodes were placed on the skin of the subject at standard positions[49] for each of the six muscles to be recorded. The skin was prepared prior to electrode application by cleaning the area with an alcohol swab and allowing time for the area to dry. The participant was then seated and the dominant lower extremity secured in the appropriate limb attachment on the Biodex Dynamometer. For both quadriceps and hamstring MVIC measurements, the knee attachment was used. The subject was positioned with 75° knee flexion, the backrest of the dynamometer seat was inclined to promote a hip joint angle of 100°. The mechanical axis of the dynamometer was aligned with the lateral femoral condyle. For gastrocnemius MVIC measurements, the combination ankle plate attachment with footrest adapter and limb support pad were utilized. The backrest was positioned as stated above. The subject's knee was supported via the limb support pad promoting a knee angle of 20° flexion. The ankle attachment was set at 0° tilt with subject's ankle positioned at 10° of plantarflexion. The mechanical axis of the dynamometer was aligned with the talus. Stabilization straps were used to secure the chest and thigh. The subject was asked to perform a series of three five-second MVICs with one-minute rest periods between each set for all the muscle groups. The muscle activity was captured via EMG recording and averaged for a net output of isometric torque.

Next, the subject performed two landing tasks. The order in which these tasks were performed was counterbalanced between the subjects. The first subject's order was determined by coin flip and subsequent subjects performed the tasks in alternating order. The drop-rebound jump landing task required the subject to stand with her feet shoulder width apart and toes aligned with the edge of the 40 cm high platform. The subject then jumped forward landing on both lower extremities and immediately rebounded into a vertical jump. Subjects were asked to jump "as high as they could" on the rebound and "land softly" on both lower extremities to complete the task. The other landing task involved a forward jump from a distance of 45% of subject's height from the landing marker. A 10 cm high by 15 cm wide box was placed halfway between the subject and the landing marker. The box size was not difficult to maneuver over; however, it encouraged a more vertical component to the task. Subjects jumped over the box, traveled a distance of 45% her height, and landed on both lower extremities on a tile marked with an 'X'.

To ensure safety for the subject, a padded table (secured to the floor) was placed in front of or beside the subject so that they could "catch" themselves should they have felt the need to do so. This was found to be adequate in ensuring balance recovery during previous studies.[47,48] Each subject had three practice trials for each landing task to become acquainted and comfortable with the technique.

For testing, subjects completed five trials of each landing task for each of the four heel lift heights (40 trials total). To prevent fatigue subjects rested 30 seconds between trials and five minutes between heel lift height conditions (during the time it took to change the heel lift on the shoe). No subjects reported or showed signs of fatigue or soreness during or after performance of these tasks. Furthermore, no specific risks or benefits to individual subjects were noted throughout the study process.

During the landing tasks, EMG data were collected via the surface electrodes on the six muscle groups and recorded using MyoResearch XP data acquisition software (Noraxon, Scottsdale, AZ). The pressure-sensitive footswitches were integrated with this software. When initial contact occurred during the landing tasks, the footswitches registered an event that provided a standardized marker to be used when analyzing the EMG data.

DATA REDUCTION AND STATISTICAL METHODS

The EMG data were reduced within the acquisition/analysis software. Event markers were created in the program based on the initial contact registered by the footswitches to identify the start of each trial. The five trials for each task were averaged and custom buffers created, thereby allowing the investigator to identify the dependent variables. Signal smoothing using a root mean square algorithm at 50ms and full-wave rectification were used to process the data. Average and peak muscle activation and time to achieve peak muscle activation data were then analyzed within the software. These data were downloaded and organized into a spreadsheet (Microsoft Excel (2015), Redmond, WA). EMG data were then normalized to a percent of the MVIC. After data reduction, statistical analyses were completed with a commercially available statistical software package (SPSS 18.0; Chicago, IL). Separate repeated measures (randomized block) analysis of variances (ANOVA) were utilized to determine the influence of additional heel lift on the magnitude of muscle contraction at initial contact and peak activity and time to achieve peak muscle activity for each muscle for each landing task. When appropriate, post hoc testing using one-tailed paired t-tests were performed to identify any significant differences in the dependent variables between the heel lift conditions. Alpha levels were set a-priori at $p < 0.05$.

Table 1. *Subject demographic data ($n = 60$).*

	Average	SD
Age (yr)	19.94	2.01
Height (cm)	168.32	32.16
Weight (kg)	62.47	10.22
Activity (hr/week)	6.38	2.53

SD-standard deviation

Table 2. *Average EMG activity per muscle during forward jump.*

Muscle	Lift (mm)	Means[†]	SD	Ave mag p-values
VMO	0	1.4582	2.1760	0.378
	12	1.1836	0.5984	
	18	1.1874	0.6492	
	24	1.2052	0.5825	
VL	0	1.0455	0.5353	0.082
	12	1.0444	0.4936	
	18	1.1156	0.5851	
	24	1.1015	0.5065	
ST	0	0.4439	0.3410	0.61
	12	0.4112	0.2777	
	18	0.4025	0.3142	
	24	0.4673	0.6603	
BF	0	0.6991	0.7659	0.447
	12	0.6736	0.7460	
	18	0.6397	0.6585	
	24	0.6919	0.8336	
MG	0	0.7674	0.4206	0.785
	12	0.7830	0.5483	
	18	0.7713	0.4723	
	24	0.8031	0.4969	
LG	0	1.2599	1.1293	0.587
	12	1.1570	1.0667	
	18	1.1760	1.0904	
	24	1.1575	0.9550	

† - means represent the normalized EMG data
SD-standard deviation; Ave-average; mag-magnitude; VMO-vastus medialis; VL-vastus lateralis; ST-semitendinosus, BF-biceps femoris, MG-medial gastrocnemius, LG-lateral gastrocnemius

RESULTS

Sixty recreationally active females participated. Five subjects' data were not able to be used due to poor EMG or footswitch recordings. Table 1 presents demographic information. There were no signficant differences in the average magnitude of muscle activity, peak magnitude, or time to achieve peak magnitude with the four different heel lift heights during the forward jump (Table 2, 3, and 4 respectively) and drop-rebound jump (Table 5, 6, and 7 respectively) manuevers with one exception. A significant difference was found in the time to achieve peak magnitude of muscle activity in the semitendinosis muscle during a forward jump landing ($p = .024$). Post hoc analysis determined that significant differences existed between both the 18mm and 24mm heel lift height when compared to 0mm (Figure 1).

Table 3. *Peak EMG activity per muscle during forward jump.*

Muscle	Lift (mm)	Means†	SD	Peak mag p-values
VMO	0	4.1506	8.1211	0.324
	12	3.0929	1.6322	
	18	3.0544	1.9353	
	24	3.1937	1.9076	
VL	0	2.5690	1.2916	0.291
	12	2.6652	1.3435	
	18	2.7918	1.8140	
	24	2.7709	1.4365	
ST	0	1.0716	0.9476	0.355
	12	1.0210	0.8029	
	18	1.0924	1.1114	
	24	1.3142	2.1312	
BF	0	1.9562	2.9291	0.162
	12	2.0578	3.3342	
	18	1.9444	2.9331	
	24	2.3631	4.0588	
MG	0	2.1194	1.1991	0.102
	12	2.4853	2.0865	
	18	2.3638	1.6378	
	24	2.4793	1.8056	
LG	0	3.2240	3.0276	0.529
	12	3.1979	2.8806	
	18	3.3873	3.2605	
	24	3.5134	3.1249	

† - means represent the normalized EMG data
SD-standard deviation; mag-magnitude;
VMO-vastus medialis; VL-vastus lateralis;
ST- semitendinosus,
BF-biceps femoris, MG-medial gastrocnemius,
LG-lateral gastrocnemius

Table 4. *Time to achieve peak EMG activity per muscle during forward jump.*

Muscle	Lift (mm)	Means†	SD	TTP p-values
VMO	0	0.0675	0.035	0.192
	12	0.0767	0.044	
	18	0.0725	0.042	
	24	0.0771	0.053	
VL	0	0.0776	0.038	0.283
	12	0.0797	0.04	
	18	0.0779	0.042	
	24	0.0898	0.076	
ST	0	0.0725	0.061	0.024*
	12	0.063	0.058	
	18	0.0524	0.05	
	24	0.0506	0.055	
BF	0	0.0861	0.044	0.336
	12	0.1015	0.098	
	18	0.083	0.039	
	24	0.0843	0.088	
MG	0	0.0358	0.036	0.06
	12	0.0405	0.041	
	18	0.0397	0.039	
	24	0.0642	0.12	
LG	0	0.0643	0.053	0.454
	12	0.0541	0.044	
	18	0.0508	0.038	
	24	0.0543	0.074	

† - means represent time in milliseconds
* - significant difference at p<0.05 (with ANOVA)
SD-standard deviation; TTP-time to achieve peak EMG activity; VMO-vastus medialis; VL-vastus lateralis;
ST- semitendinosus, BF-biceps femoris,
MG-medial gastrocnemius, LG-lateral gastrocnemius

DISCUSSION

The purpose of this study was to investigate the influence of heel lift height on muscle activity during forward jump and drop-rebound landing tasks. The semitendinosus was found to achieve a faster time to peak muscle activation during the forward jump landing task with the addition of a 18mm or 24mm heel lift compared to the control condition of 0mm. A trend was identified demonstrating increased hamstring peak magnitude (normalized EMG output for semitendinosus increased from 1.0716 at 0mm to 1.3142 at 24mm and biceps femoris from 1.9562 at 0mm to 2.3631 at 24mm) and a slower time to achieve peak magnitude for the quadriceps musculature (vastus lateralis time to peak increased from 0.0776 ms to 0.0898 ms); however, these results were not statistically significant.

Investigation of the utilization of heel lifts to influence landing maneuvers continues to remain novel research. Thus, there is a paucity of literature to directly compare the results of this study. One study found that the addition of a 24 mm heel lift significantly increased knee flexion at initial contact and peak knee flexion as well as slowed the rate of joint excursion when landing from a forward jump.[47] In a follow up publication, it was further demonstrated that utilization of a 24mm heel lift caused a decrease in vertical ground reaction force (vGRF) with a forward jump, but not during a drop-rebound jumping

Table 5. *Average EMG activity per muscle during drop rebound.*

Muscle	Lift (mm)	Means†	SD	Ave mag p-values
VMO	0	2.9352	4.3895	0.397
	12	2.4046	1.1046	
	18	2.4794	1.2487	
	24	2.3868	1.0985	
VL	0	2.2209	1.0530	0.582
	12	2.2662	1.0911	
	18	2.3675	1.3674	
	24	2.3160	1.6380	
ST	0	0.8388	0.7613	0.583
	12	0.8444	0.8483	
	18	0.7984	0.7572	
	24	0.8647	1.0258	
BF	0	1.5473	1.8031	0.271
	12	1.5914	2.1502	
	18	1.4696	1.7124	
	24	1.8021	3.2398	
MG	0	1.9861	1.1863	0.270
	12	1.9138	1.0253	
	18	1.9423	1.0600	
	24	1.8381	0.8457	
LG	0	3.2938	2.7361	0.437
	12	3.3134	2.8376	
	18	3.2797	2.8642	
	24	3.1350	2.3446	

† - means represent time in milliseconds
SD-standard deviation; Ave-average; mag-magnitude; VMO-vastus medialis; VL-vastus lateralis; ST-semitendinosus, BF-biceps femoris, MG-medial gastrocnemius, LG-lateral gastrocnemius

Table 6. *Peak EMG activity per muscle during drop rebound.*

Muscle	Lift (mm)	Means†	SD	Peak mag p-values
VMO	0	5.0182	6.9933	0.458
	12	4.1723	2.0645	
	18	4.4232	2.3089	
	24	4.1406	1.8840	
VL	0	3.9563	1.9526	0.572
	12	4.0659	2.5810	
	18	4.5840	3.7688	
	24	4.4415	6.1703	
ST	0	1.7788	2.6139	0.511
	12	1.7762	2.7903	
	18	1.8104	2.4943	
	24	2.0072	3.8871	
BF	0	3.6110	4.5765	0.350
	12	3.7469	4.8964	
	18	3.6626	4.6401	
	24	4.5324	8.8576	
MG	0	4.4609	4.7973	0.355
	12	4.3048	3.8896	
	18	4.7154	4.4551	
	24	4.0803	2.9563	
LG	0	7.0778	7.2751	0.569
	12	7.5654	8.3003	
	18	7.8627	10.2347	
	24	7.1170	6.1623	

† - means represent time in milliseconds
SD-standard deviation; mag-magnitude; VMO-vastus medialis; VL-vastus lateralis; ST- semitendinosus, BF-biceps femoris, MG-medial gastrocnemius, LG-lateral gastrocnemius

maneuver.[48] These results collectively suggest that the addition of heel lifts favorably alters lower extremity biomechanics during a forward jump landing task. However, the role of muscle activity in these biomechanical responses remains unclear.

It is generally accepted that an imbalanced hamstring to quadriceps ratio and a delayed onset of hamstring time to peak torque are both ACL risk factors.[21,50] Huston and colleagues[21] found that Division I female athletes took significantly longer to produce hamstring peak torque and relied on more of their quadriceps musculature in response to anterior tibial translation when compared to their male counterparts. As such, a faster time to peak magnitude of the semitendinosus through the utilization of a heel lift has been speculated to be ideal when attempting to maximize protection of the ACL. Although not found to be statistically significant, trends were identified in this current study for slower time to peak magnitude in the quadriceps musculature and increased magnitude of hamstring activity during landing tasks.

Hong and colleagues[44] investigated the effects of footwear with differing heel heights (0cm, 3.8cm, and 7.6cm) on EMG responses throughout the lower extremity while walking. They found that elevated heel heights reduced load of the quadriceps musculature, supporting the trends of the authors' current research that the quadriceps musculature may be influenced through the utilization of added heel lift height. However, the reduction of quadriceps activation with elevated heel heights is inconsistent

Muscle	Lift (mm)	Means†	SD	TTP p-values
VMO	0	0.1764	0.1342	0.550
	12	0.2058	0.1529	
	18	0.1895	0.1399	
	24	0.1866	0.1444	
VL	0	0.2153	0.1555	0.931
	12	0.2245	0.1487	
	18	0.2264	0.1490	
	24	0.2245	0.1489	
ST	0	0.1916	0.1756	0.458
	12	0.1721	0.1394	
	18	0.1847	0.1598	
	24	0.2092	0.1986	
BF	0	0.1793	0.1509	0.400
	12	0.1681	0.1341	
	18	0.1741	0.1368	
	24	0.1990	0.1733	
MG	0	0.2185	0.1670	0.584
	12	0.2430	0.1771	
	18	0.2393	0.1689	
	24	0.2258	0.1722	
LG	0	0.2459	0.1785	0.750
	12	0.2637	0.1803	
	18	0.2620	0.1720	
	24	0.2477	0.1722	

Table 7. *Time to achieve peak EMG activity per muscle during drop rebound.*

† - means represent time in milliseconds
SD-standard deviation; TTP-time to peak; VMO-vastus medialis; VL-vastus lateralis; ST- semitendinosus, BF-biceps femoris, MG-medial gastrocnemius, LG-lateral gastrocnemius

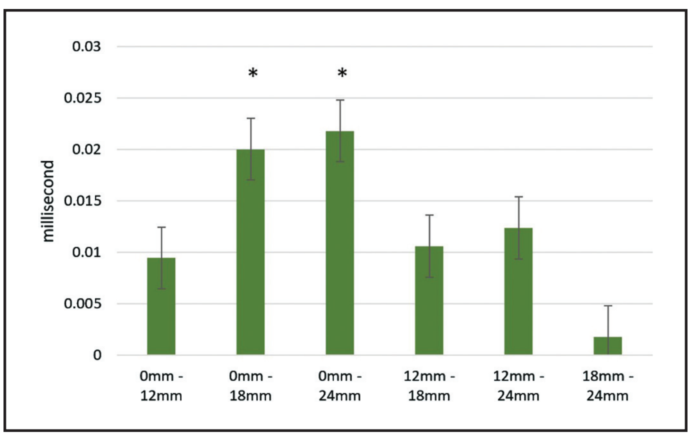

Figure 1. *Post hoc results for Time to Achievement of Peak EMG activity (TTP) in semitendinosis during forward hop *Significant difference from 0mm heel lift FH-forward hop; TTP-time to peak EMG magnitude; ST-semitendinosis*

throughout the literature, with reports of increased quadriceps muscle EMG while utilizing a heel lift during gait.[51,52,53] These publications utilized larger heel lift heights (range of 4-10 cm) compared to the highest heel lift height used in the present study of 24mm (2.4 cm). However, it is possible that extreme heel lift heights would be deleterious from a biomechanical perspective, possibly even increasing the likelihood of injury. Determination of an optimal heel lift height has yet to be determined and requires further research.

As demonstrated in the current study and previous publications, there were no statistically significant differences in joint kinematics or EMG activity observed during drop-rebound jump landing tasks with the utilization of heel height lifts.[47,48] This could be attributed to a more forefoot-based landing strategy during the rebound jump. It has been demonstrated in other research that subjects landing from a more vertically oriented jump demonstrate a larger degree of ankle plantarflexion and utilize a forefoot landing strategy.[56,57,58] Thus, the subjects in this study may have not had enough heel contact with the ground to utilize the effects of the increased heel lift height. The current findings suggest that the only possible protective benefit of heel lift utilization occurs only with forward jump tasks, and with greater heel lift heights (18mm and 24mm). It is unknown whether these effects would apply to other dynamic, sport specific maneuvers that have yet to be studied.

One limitation of this study was that a limited number of lower extremity muscles were assessed during the landing procedures. For example, gluteus medius has been investigated in other studies for its role in knee kinematics during landing.[59,60] The current project did not identify significant alterations in the activation of six muscles under different heel lift conditions. However, it is possible that other muscles could play a role in promoting the kinematic changes seen in past research using the same conditions.

No data were gathered on ankle kinematics or other musculature of the ankle. Therefore, the influence of added heel lift height on the ankle during the selected landing tasks is unknown. Researchers investigating muscle response to heel lifts during gait have reported decreased amplitude of the gastrocnemius muscle EMG response[42,61] and increased plantarflexion.[44,47] The current study found no significant changes in gastrocnemius activity during either landing maneuver. More research is warranted to further investigate these relationships.

At this time, the authors of this study are unable to predict any potential negative effects from using elevated heel lift heights in athletic shoe wear. There is very little information on the use of heel lifts in landing activities and, thus, there is no data suggesting whether an elevated heel could have a negative impact on performance, joint integrity, or the overall safety of the individual. Additionally, it is not possible to comment on how elevated heel lift height might alter other athletic activities, such as running or cutting. Again, future research and longitudinal studies would be necessary to discover if any problems would arise from the use of heel lifts.

Future research on the effect of heel lift height on landing mechanics is warranted. Positive knee kinematic changes and ground reaction force values have been identified when using heel lifts during forward jump maneuvers.[47,48] Future research should investigate other biomechanical factors such as recruitment order and onset timing of key muscle groups. Sports maneuvers such as pivoting and cutting have also been associated with non-contact ACL injury risk.[11,12,17] It would be beneficial to determine if the use of heel lifts would show similar kinematic effects as those seen with forward jump maneuvers. It would also be prudent to identify the impact that heel lifts would have at the ankle, hip, and trunk during sports maneuvers. Research could continue to investigate ACL injury risk reduction while also identifying any potentially adverse responses generated by the additional heel lift height.

CONCLUSION

ACL injuries remain one of the most frequent knee injuries in physically active individuals, especially in the female population.[1-3,4,5] Previous studies have suggested that the utilization of heel lifts to positively influence biomechanics may be of potential benefit.[47,48] In the current study, there were no significant differences found in the muscle recruitment under the various heel lift conditions with the exception of the semitendinosus time to achieve peak magnitude. By influencing the semitendinosis to achieve peak magnitude more quickly, an athlete may reap protective benefits and decrease ACL injury risk. The clinical relevance of these findings remains unknown. Further research is warranted.

REFERENCES

1. Hootman JM, Dick R, Agel J. Epidemiology of collegiate injuries for 15 sports: Summary and recommendations for injury prevention initiatives. *J Athl Train.* 2007;42(2):311-319.
2. Agel J, Rockwood T, Klossner D. Collegiate ACL injury rates across 15 sports: National Collegiate Athletic Association injury surveillance system data update (2004-2005 through 2012-2013). *Clin J Sport Med*. 2016;26(6):518-523.
3. Agel J, Arendt E, Bershadsky B. Anterior cruciate ligament injury in national collegiate athletic association basketball and soccer: A 13-year review. *Am J Sports Med.* 2005; 33(4):524-530.
4. Walden M, Hagglund M, Magnusson H, Ekstrand J. Anterior cruciate ligament injury in elite football: a prospective three-cohort study. *Knee Surg Sports Traumatol Arthrosc.* 2011;19:11-19.
5. Montalvo AM, Schneider DK, Webster KE, Yut L, Galloway MT, et al. Anterior cruciate ligament injury risk in sports: A systematic review and meta-analysis of injury incidence by sex and sports classification. *J Athl Train*. 2019;54:472-482.
6. Griffin LY, Agel J, Albohm MJ, et al. Noncontact anterior cruciate ligament injuries: Risk factors and prevention strategies. *J Am Acad Orthop Surg*. 2000;8(3):141-150.
7. Myer GD, Ford KR, Khoury J, Succop P, Hewett TE. Biomechanics laboratory-based prediction algorithm to identify female athletes with high knee loads that increase risk of ACL injury. *Br J Sports Med.* 2011;45(4):245-252.
8. Hewett TE, Myer GD, Ford KR, et al. Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: A prospective study. *Am J Sports Med.* 2005;33(4):492-501.
9. Paterno MV, Schmitt LC, Ford KR, et al. Biomechanical measures during landing and postural stability predict second anterior cruciate ligament injury after anterior cruciate ligament reconstruction and return to sport. *Am J Sports Med.* 2010;38(10):1968-1978.
10. Pfeiffer RP, Shea KG, Roberts D, Grandstand S, Bond L. Lack of effect of a knee ligament injury prevention program on the incidence of noncontact anterior

cruciate ligament injury. *J Bone Joint Surg Am.* 2006;88(A):1769-1774.

11. Boden BP, Dean GS, Feagin JA, Garrett WE. Mechanisms of anterior cruciate ligament injury. *Orthopedics.* 2000;23(6):573-578.
12. Hewett TE, Ford KR, Hoogenboom BJ, Myer GD. Understanding and preventing ACL injuries: Current biomechanical and epidemiologic considerations – update 2010. *N Am J Sports Phys Ther*. 2010;5(4): 234-251.
13. Colby S, Francisco A, Yu B, Kirkendall D, Finch M, Garrett W. Electromyographic and kinematic analysis of cutting maneuvers. Implications for anterior cruciate ligament injury. *Am J Sports Med*. 2000;28(2):234-240.
14. Huston LJ, Vibert B, Ashton-Miller JA, Wojtys EM. Gender differences in knee angle when landing from a drop-jump. *Am J Knee Surg*. 2001;14(4):215-219.
15. Myer GD, Ford KR, Brent JL, Hewett TE. Differential neuromuscular training effects on ACL injury risk factors in "high-risk" versus "low-risk" athletes. *BMC Musculoskelet Disord.* 2007;8(39):1-7.
16. Fox AS, Bonacci J, McLean SG, Saunders N. Efficacy of ACL injury risk screening methods in identifying high-risk landing patterns during a sport-specific task. *Scand J Med Sci Sports.* 2016; 27(5): 525-534.
17. Olsen OE, Myklebust G, Engebretsen L, et al. Injury mechanisms for anterior cruciate ligament injuries in team handball: a systematic video analysis. *Am J Sports Med.* 2004;32:1002-1012.
18. Pollard CD, Sigward SM, Powers CM. Limited hip and knee flexion during landing is associated with increased frontal plane knee motions and moments. *Clin Biomech.* 2009;25(2010):142-146.
19. Barendrecht M, Lezeman H, Duysens J, Smits-Engelsman B. Neuromuscular training improves knee kinematics, in particular valgus aligned adolescent team handball players of both sexes. *J Strength Cond Res.* 2011;25(3):575-584.
20. Hewett TE, Stroupe AL, Nance TA, Noyes FR. Plyometric training in female athletes: Decreased impact forces and increased hamstring torques. *Am J Sports Med.* 1996;24(6):765-773.
21. Huston LJ, Wojtys. Muscular performance characteristics in elite female athletes. *Am J Sports Med.* 1996; 24(6):427-436.
22. Li G, Rudy TW, Sakane M, Kanamori A, Ma CB, Woo SL-Y. The importance of quadriceps and hamstring muscle loading on knee kinematics and in-situ forces in the ACL. *J Biomech*. 1999;32:395-400.
23. Withrow TJ, Huston LJ, Wojtys EM, Ashton-Miller JA. The relationship between quadriceps muscle force, knee flexion and anterior cruciate ligament strain in an in vitro simulated jump landing. *Am J Sports Med.* 2006;34:269-274.
24. Podraza JT, White SC. Effect of knee flexion angle on ground reaction forces, knee moments and muscle co-contraction during an impact-like deceleration landing: Implications for the non-contact mechanism of ACL injury. *The Knee.* 2010;17:291-295.
25. DeMorat G, Weinhold P, Blackburn T, Chudik S, Garrett W. Aggressive quadriceps loading can induce noncontact anterior cruciate ligament injury. *Am J Sports Med*. 2004;32(2):477-483.
26. Myer GD, Ford KR, Barber Foss KD, Liu C, Nick TG, Hewett T. The relationship of hamstrings and quadriceps strength to anterior cruciate ligament injury in female athletes. *Clin J Sports Med.* 2009;19(1):3-8.
27. Noyes FR, Barber-Westin SD, Smith ST, Campbell T. A training program to improve neuromuscular and performance indices in female high school soccer players. *J. Strength Cond. Res.* 2013; 27(2):340-351.
28. Noyes FR, Barber-Westin SD, Smith ST, Campbell T. A training program to improve neuromuscular and performance indices in female high school volleyball players. *J Strength Cond Res.* 2011;25(8):2151-2160.
29. Noyes FR, Barber-Westin SD, Smith ST, Campbell T, Garrison T. A training program to improve neuromuscular and performance indices in female high school basketball players. *J Strength Cond Res.* 2012;26(3):709-719.
30. Campbell CJ, Carson JD, Diaconesu ED, et al. Canadian academy of sport and exercise medicine position statement: Neuromuscular training programs can decrease anterior cruciate ligament injuries in youth soccer players. *J Strength Cond Res.* 2014;24:263-267.
31. Noyes FR, Barber-Westin SD. Neuromuscular retraining in female adolescent athletes: Effect on athletic performance indices and noncontact anterior cruciate ligament injury rates. *Sports.* 2015;3:56-76.
32. Greska EK, Cortes N, Van Lunen BL, Onate JA. A feedback inclusive neuromuscular training program alters frontal plane kinematics. *J Strength Cond Res.* 2012;26(6):1609-1619.
33. Kiani A, Hellquist E, Ahlqvist K, et al. Prevention of soccer-related knee injuries in teenaged girls. *Arch Intern Med.* 2010;170(1):43-49.
34. Myer GD, Ford KR, Brent JL, Hewett TE. The effects of plyometric vs dynamic stabilization and balance training on power, balance, and landing force in female athletes. *J Strength Cond Res*. 2006a;20(2):345-353.
35. Noyes FR, Barber Westin SD. Anterior cruciate ligament injury prevention training in female athletes: A systematic review of injury reduction and

results of athletic performance tests. *Sports Health.* 2012.4(1):36-46.

36. Irmischer BS, Harris C, Pfeiffer RP, DeBeliso MA, Shea KG. Effects of a knee ligament injury prevention exercise program on impact forces in women. *J Strength Cond Res.* 2004;18(4):703-707.
37. Myklebust G, Engebretsen L, Braekken IH, Skjolberg A, Olsen OE, Bahr R. Prevention of anterior cruciate ligament injuries in female team handball players: a prospective intervention study over three seasons. *Clin J Sports Med*. 2003;13(2):71-78.
38. Vescovi JD, VanHeest JL. Effects of an anterior cruciate ligament injury prevention program on performance in adolescent female soccer players. *Scand J Med Sci Sports*. 2010;20:394-402.
39. Blachette MG, Brault JR, Powers CM. The influence of heel height on utilized coefficient of friction during walking. *Gait Posture.* 2011;34:107-110.
40. Stefanyshyn DJ, Nigg BM, Fisher V, O'Flynn B, Li W. The influence of high heeled shoes on kinematics, kinetics, and muscle EMG on normal female gait. *J Appl Biomech.* 2000;16:309-319.
41. Esenyel M, Walsh K, Walden JG, Gitter A. Kinetics of high-heeled gait. *J Am Podiatr Med Assoc.* 2003; 93(1):27-32.
42. Ho KY, Blanchette MG, Powers CM. The influence of heel height on patellofemoral joint kinetics during walking. *Gait Posture.* 2012;36:271-275.
43. Hong W, Lee Y, Lin Y, Tang SF, Chen H. Effect of shoe heel height and total-contact insert on muscle loading and foot stability while walking. *Foot Ankle Int.* 2013;34(2):273-281.
44. Kim MH, Yi CH, Yoo WG, Choi BR. EMG and kinematics analysis of the trunk and lower extremity during the sit-to-stand task while wearing shoes with different heel heights in healthy young women. *Hum Mov Sci.* 2011;30:596-605.
45. Hong WH, Lee YH, Chen HC, Pei YC, Wu CY. Influence of heel height and shoe insert of comfort perception and biomechanical performance of young female adults during walking. *Foot Ankle Int.* 2005;26(12):1042-1048.
46. Cronin NJ. The effects of high heeled shoes on female gait. *J Electromyogr Kinesiol.* 2014;24:258-263.
47. Lindenberg KM, Carcia CR, Phelps AL, Martin RL, Burrows AM. The influence of heel height on sagittal plane knee kinematics during landing tasks in recreationally active and athletic collegiate females. *Int J Sports Phys Ther.* 2011;6(3):186-198.
48. Lindenberg KM, Carcia CR. The influence of heel height on vertical ground reaction force during landing tasks in recreationally active and athletic collegiate females. *Int J Sports Phys Ther.* 2013; 8(1):1-8.
49. SENIAM project. European Recommendations for Surface ElectroMyoGraphy. Sensor Locations. www.seniam.org. Accessed October 8, 2019.
50. Lephart SM, Ferris CM, Riemann BL, Myers JB, Fu FH. Gender differences in strength and lower extremity kinematics during landing. *Clin Orthop Relat Res.* 2002;401:162-169.
51. Mika A, Oleksy L, Mika P, Marchewka A, Clark BC. The influence of heel height on lower extremity kinematics and leg muscle activity during gait in young and middle-aged women. *Gait Posture*. 2012b;35(4):677–80.
52. Simonsen EB, Svendsen MB, Norreslet A, Baldvinsson HK, Heilskov-Hansen T, Larsen PK, et al. Walking on high heels changes muscle activity and the dynamics of human walking significantly. *J Appl Biomech.* 2012;28(1):20–8.
53. Stefanyshyn DJ, Nigg BM, Fisher V, O'Flynn B, Liu W. The influence of high heeled shoes on kinematics, kinetics, and muscle EMG of normal female gait. *J Appl Biomech.* 2000;16(3):309–19.
54. Blanchette MG, Brault JR, Powers CM. The influence of heel height on utilized coefficient of friction during walking. *Gait Posture.* 2011;34(1):107–10.
55. Ebbeling CJ, Hamill J, Crussemeyer JA. Lower extremity mechanics and energy cost of walking in high-heeled shoes. *J Orthop Sports Phys Ther.* 1994;19(4):190–6.
56. Brown C, Padua D, Marshall SW, Guskiewicz K. Individuals with mechanical ankle instability exhibit different motion patterns than those with functional ankle instability and ankle sprain copers. *Clin Biomech*. 2008;23:822-831.
57. Cortes N, Onate J, Abrantes J, Gagen L, Dowling E, van Lunen B. Effects of gender and foot-landing techniques on lower extremity kinematics during drop- jump landings. *J Applied Biomech*. 2007;23:289-299.
58. DiStefano LJ, Padua DA, Brown CN, Guskiewicz KM. Lower extremity kinematics and ground reaction forces after prophylactic lace-up ankle bracing. *J Athl Train*. 2008;43:234-241.
59. Jacobs CA, Uhl TL, Mattacola CG, Shapiro R, Rayens WS. Hip abductor function and lower extremity landing kinematics: sex differences. *J Athl Train*. 2007;42(1):76-83.
60. Lawrence RK III, Kernozek TW, Miller EJ, Torry MR, Reuteman P. Influences of hip external rotation strength on knee mechanics during single-leg drop landings in females. *Clin Biomech*. 2008;23(6):806-813.
61. Lee KH, Shieh JC, Matteliano A, Smiehorowski T. Electromyographic changes of leg muscles with heel lifts in women: therapeutic implications. *Arch Phys Med Rehabil.* 1990;71(1):31-33.